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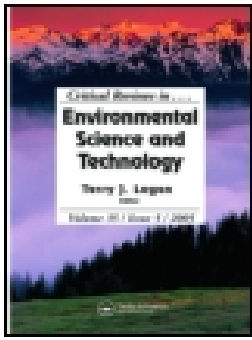
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Medical waste: Current challenges and future opportunities for sustainable management

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ABSTRACT

Countries worldwide are struggling to develop strategies and infrastructure for appropriate disposal of the increasing medical waste generated by the COVID-19 pandemic. This study examines the available knowledge and current practices in medical/healthcare waste management worldwide, particularly in countries with transitional economies,
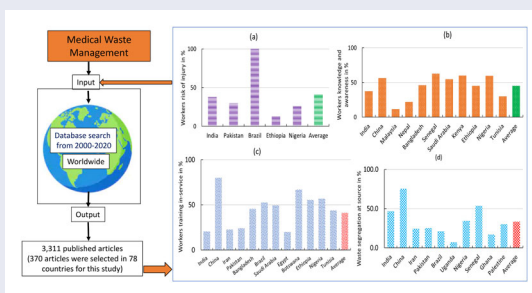
including the dependence of medical waste generation rate on various socioeconomic and environmental parameters. Here, we conducted a meta-analysis of medical and healthcare waste management practices in 78 countries. We identified impediments and challenges facing the integration of medical waste management into a prospective circular economy according to statistical correlations with human development index (HDI), life expectancy (LE), healthcare expenditure (HE) per capita of gross domestic product (GDP), and environmental performance index (EPI). The results highlight the importance of knowledge and awareness of best practices for infection and injury prevention for waste management among workers. An average of 38.9% of medical waste was segregated for proper management, and only 41% of workers were trained in-service for medical waste disposal. Plastic materials constituted approximately 35% of medical waste, presenting an opportunity for sustainable resource recovery and recycling. It is imperative for all countries to adopt environmentally sustainable management of medical waste to prevent catastrophic stockpiling of infectious waste during and after pandemics. Additionally, we present an outline for future studies on medical waste generation rate and various socioeconomic and environmental parameters that should be investigated in future work to promulgate an inventory of the database for sustainable management of medical/healthcare waste.

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Supplemental data for this article can be accessed at publisher's website.

1. Introduction

Technological advancements in social networks, transportation, and trade have fueled global economic growth resulting in the expansion of health-care systems and a concomitant increase in demand for medical equipment and supplies (Bloom et al., 2018). Simultaneously, in many countries, unsafe disposal and mismanagement of medical waste generated in health-care settings are also growing gradually (Minoglou et al., 2017). According to the international organization, Health Care Without Harm (HCWH), the healthcare industry is considered to be the fifth-largest emitter of greenhouse gases (GHGs) worldwide, equivalent to 4.4% of global net emissions (Karliner et al., 2019). The global growth rate of healthcare waste management costs are estimated to rise from $11.77 billion in 2018, to $17.89 billion in 2026 at a compound annual growth rate of 5.3% (RD Reports and Data, 2020). Many countries with economies in transition are expected to witness high growth of healthcare waste due to their strict government regulations, and the current COVID-19-pandemic (RD Reports and Data, 2020). In 2020, the already unsustainable increase in the generation and management of medical waste was suddenly exacerbated by the COVID-19-pandemic, leading to an immediate threat that if not safely and properly contained will spill over into an environmental pollution and public health crisis (Peng et al.,2020; Singh et al., 2020a; Singh et al., 2020b).

Studies have reported that before the COVID-19 pandemic, over half of the world's population was already at risk of threats from environmental pollution and public health due to unsafe disposal of healthcare waste (Pachauri et al., 2019; Harhay et al., 2009). Additionally, unsafe disposal of medical waste in countries with economies in transition is also considered to be a severe cause of infectious diseases responsible for 0.4-1 million deaths each year (Williams et al., 2019). According to the World Health Organization (WHO), the number of new infections of hepatitis B, hepatitis C, and HIV caused by contaminated syringes have been 21 million, 2 million, and 260,000, representing almost 32%, 40%, and 5% of all new infections, respectively (WHO, 2018). In addition, a study of 24 countries with economies in transition showed that 18% to 64% of healthcare settings do not use proper medical waste disposal techniques. The report concluded that, on average, only 58% of the facilities from 24 low-income countries had adequate safe disposal of healthcare waste. Among all member countries, the South-East Asia Region (SEARO) including Bangladesh, Bhutan, India, Nepal, Sri Lanka, and Timor-Leste of WHO, showed the lowest safe disposal setting, with only 44% of the facilities having a system for safely collecting, disposing, and destroying healthcare waste. These outcomes complicate health challenges in resource-limited settings with a high burden of disease in countries with economies in transition (WHO, 2015).

The waste generated in healthcare settings or contaminated by the secretions of medical patients through blood, body fluids, or other media, is considered medical waste and is often referred to as medical waste, mostly regulated by national environmental and health departments (EPA, 2020a). Historically, in the US, the concern for potential health risks from medical waste was first discussed in the 1980s, when medical wastes were shown up in the oceans and on the east coast beaches and nature trails, which led the US government to enact the Medical Waste Tracking Act (MWTA) of 1988. This included guidelines for defining medical waste together with the waste tracking system, standards for separating, packing, storing and labeling of waste; and imposition of penalties for not maintaining records of the medical waste generated (EPA, 2020b). The efficacious outcomes of MWTA 1988 were later enforced in each county to create its standard guidelines for medical waste management.

Most of the medical waste generated from healthcare settings is not always hazardous or more dangerous than general household waste. However, it depends on the type of medical waste that represents different health risk levels (WHO, 2018). For example, infectious waste, which accounts for 15%-25% of the total medical waste, including sharp objects, body parts, chemical or expired medicines, and radioactive and cytotoxic waste. The details are shown in Table 1 (WHO, 2019; WHO, 2020a).

Incineration and sanitary landfills are the most common methods for medical waste management worldwide (Hong et al., 2018). Before 1997, more than 90% of medical waste in the US was incinerated, which was one of the main sources (third largest) of dioxin emissions into the air (EPA, 2020c). This led the U.S. Environmental Protection Agency (EPA) to implement stringent emission standards for medical waste incinerators under the Hospital Medical Infectious Waste Incinerator standards, which took more than a decade for the government to effectively enforce and was approved in May 2013 (EPA, 2020d). However, incinerators are still the main treatment method for medical waste in most countries with transitional economies, where more than 90% of the medical waste goes to open landfills or is incinerated without the abatement devices that capture pollutants such as dioxins and heavy metals after the burning of the waste (Liu et al., 2018). Autoclaving, a heat-based, safe, and efficient treatment process is the second most popular method for medical waste treatment; however, its use is still limited to very few countries because of its economic feasibility and the appearance of the treated waste (WHO, 2020b; Ferdowsi et al., 2013). Autoclaved waste is very difficult to distinguish, which leads to a state of confusion for landfills or solid waste disposal facilities(Rożek et al., 2019). In addition, it should be noted that the volume of the waste is not reduced as with incineration. Table 1 describes the details of different treatment methods for medical waste.

Table 1. Types of healthcare/medical waste and their treatment methods (WHO, 2019; Chartier, 2014).

Waste type	Suitable treatment methods for medical waste								Description and examples
	Incineration	Chemical disinfection	Autoclave	Microwave	Encapsulation	Specially engineered landfill	Discharge to sewer systems	Other methods	
Infectious waste	✓	Partially	✓	✓	X	X	Partially	–	Waste from laboratory cultures, isolation wards, tissues (swabs), excreta from infected patients, and other pathogens containing materials.
Pathological waste	✓	X	X	X	X	X	X	–	Waste from human excreta or fluids, and fetuses including body parts.
Sharps	✓	✓	X	X	X	X	X	–	Waste from sharp materials such as needles, knives, blades, broken glasses, or plastics.
Pharmaceutical waste	✓	X	X	X	X	Partially	X	Return	Expired pharmaceuticals and waste containing used pharmaceuticals such bottles and boxes
Genotoxic waste	✓	X	X	X	X	X	X	Return	Cytostatic drugs including residues of cancer therapy, genotoxic chemicals or waste containing substances that can cause damage to DNA.
Chemical waste	Partially	X	X	X	X	X	Partially	Return	Chemical substances containing wastes such as laboratory reagents, film developer, expired disinfectants, and solvents.
Heavy metals containing waste	Partially	X	X	X	X	Partially	Partially		Waste containing metals such as batteries, broken thermometers, blood-pressure gauges, and other equipment.
Pressurized containers	✓	Partially	✓	✓	X	X	Partially		A used container such as gas cylinders, gas cartridges, aerosol cans.
Radioactive waste	✓	X	X	X	X	X	X		Radioactive waste containing unused materials after lab experiments, in contact with radioactive substances, urine and excreta from patients treated or tested with unsealed radionuclides, and other sealed sources.

√ refers to a method suitable for treatment;
X refers to methods not suitable for treatment.

The response to the COVID-19 pandemic has accelerated the demand, use, and disposal of medical waste especially discarded personal protective equipment (PPE) and single-use plastics, which is causing significant challenges for infrastructure and strategic management and waste disposal particularly in countries with economies in transition where medical waste has not been adequately regulated (Singh et al., 2020b; You et al., 2020). The adverse environmental and public health consequences of the COVID-19 pandemic have already been realized worldwide due to the limited recycling and municipal waste services (Kumar et al., 2020; Ogunseitan, 2020). Studies have shown that the collection of different solid and hazardous waste reduced by approximately 80% at the beginning of the pandemic peak of the global pandemic. Then, extra healthcare waste generated by COVID-19 might not get recycled or safely disposed of without additional infrastructure and personnel (EU & C, 2020; Langley, 2020; ACRPlus, 2020). In response, the International Solid Waste Agency (ISWA) has recommended that member countries continue the recycling activities not only for municipal solid waste but also for medical waste due to the limited storage capacity in many countries. The agency has warned that if the medical and general waste are not properly segregated at the source, the overall management system will be saddled with 30 to 50% additional waste, which may lead to a system failure, particularly in countries with economies in transition (ISWA, 2020)

Open dumping of contaminated sharps with infectious diseases, such as hepatitis, HIV/AIDS, cholera, typhoid, and respiratory complications, has been reported in many countries with economies in transition (Zafar, 2019; Khan et al.,2019; Singh et al., 2020c; Zar et al., 2020). Despite having implemented several state-level regulations and being part of many international treaties, safe and effective medical waste management systems are still lacking in many healthcare establishments, particularly in low- and middle-income countries (Convention, 2020; Oruonye & Ahmed, 2020; Dieng et al., 2020; Singh & Singh, 2018). Safe and sustainable medical waste management or wastes from healthcare products are causing concerns globally due to its environment and public health hazards. Therefore, an analysis of current medical waste management systems is an important task for national policymakers and international regulations.

In the present study, we aimed to examine the available information and current medical waste generation rates, respective and awareness of the workers responsible for the disposal of medical waste and risk of injury, workers training in-service, and source segregation, and types and compositions of medical/healthcare waste worldwide, particularly in countries with transitional economies. To this end, we have systematically reviewed and critically analyzed published information on medical/healthcare waste management in 78 countries from January 2000 to May 2020. The summarized reviewed data were

used to identify the impediments and challenges facing the integration of medical waste management into a prospective circular economy according to statistical correlations between medical waste generation rates and human development index (HDI), life expectancy (LE), healthcare expenditure (HE) per capita of gross domestic product (GDP), and environmental performance index (EPI). The current study presents an outline for future studies on medical waste generation rates and various socioeconomic and environmental parameters that should be investigated in future work to promulgate an inventory of the database for sustainable management.

2. Methods

2.1. Data collection and inclusion and exclusion criteria

We aimed to study the status and practices of medical waste management and its effects on the environment and public health based on published articles on the management of medical waste worldwide. We collected data on medical waste management from different countries from January 2000 to May 2020. The data were collected from the following sources: a) Web of Science, including the core collection, Chinese science citation database, KCI-Korean journal database, MEDLINE, Russian science citation index, and SciELO citation index; b) ProQuest health and medical databases, including Medline, consumer health, health & medical collection, healthcare administration, nursing and allied health, psychology, and public health; c) Google Scholar; and d) gray papers from various international organizations such as the World Bank and Environmental Performance Center at Yale University (World Bank, 2020; EPI, 2020). Details of the search techniques are presented in Figure 1. Electronic databases were searched comprehensively by using a combination of keywords and Boolean functions, including "medical waste" OR "healthcare waste" OR "hospital waste" OR "infectious waste" OR "clinical waste" OR "healthcare settings" OR "hazardous waste" OR "biomedical waste" OR "medical waste" AND "worldwide" OR "developing countries" OR "low-middle-income countries" AND "public health" OR "environment pollution" OR "health hazards".

The initial search yielded a total of 3,311 published articles that were further assessed for their relevance to medical waste management and practices. We followed the standard selection criteria of inclusion and exclusion measures for the searched articles based on previous studies (Grant et al., 2013; Singh et al., 2020a). Initially, the articles were screened by reading the titles and abstracts to identify the publications for further evaluation. Publications were selected for the review if they are related to medical/healthcare waste management. Articles that dealt with non-medical waste practices and focused on other issues were excluded from the study review process. The selected articles from
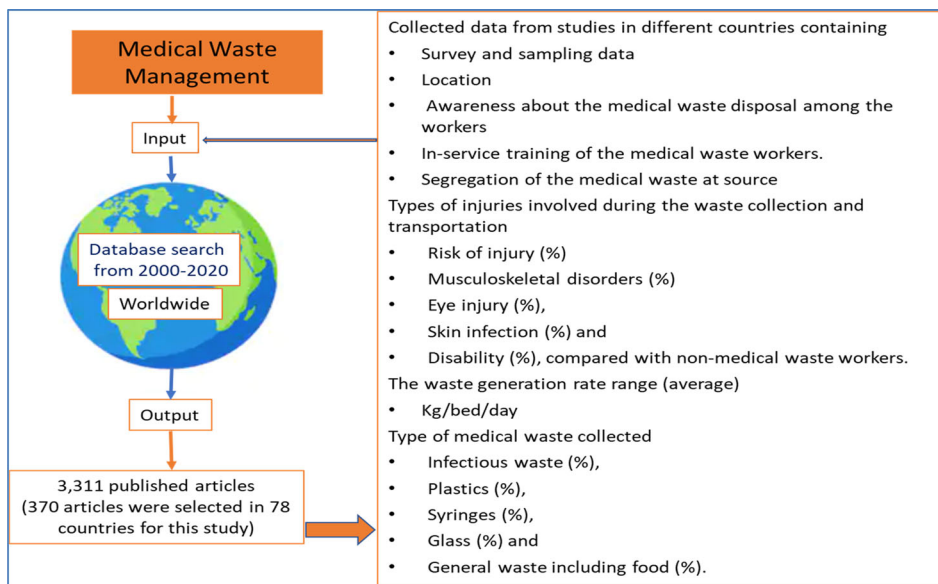
Figure 1. Diagrammatic representation of this study's methodology.

six different regions are shown in Table 2, and the detailed information of the selected articles including the title, location of the study, main outcomes, journal name, and authors' information are attached in the Excel Supplementary Information (SI) file. The published articles related to medical waste management and practices were recorded from 78 countries and subclassified into regions, including Asia with 19 countries (n = 152 papers, Latin America with 6 countries (n = 28 papers), North America with 2 countries (n = 15 papers), the Middle East with 10 countries (n = 42 papers), Europe with 18 countries (n = 60), 23 African countries (n = 71). The articles were excluded if we found discrepancies in the findings, the research methodology was not well-designed, or if the aim was not related to medical waste management. Most of the articles published in countries with economies in transition and low-income countries were based on questionnaires and modeling studies, and some lacked clarity on the types of medical waste generated. In those unclear cases, we assumed that the reported medical waste contained both infectious and general waste fractions.

2.2. The indices and statistical analysis

The environmental performance index (EPI) of controlled solid waste is referred to as the percentage of household and commercial waste generated that is collected and treated in a manner that controls environmental risks. The scores for a country include recycling, composting, anaerobic digestion, incineration, or disposal in a sanitary landfill. Data of this index are

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Table 2. Numbers of studies in different regions and countries published from January 2000 to May 2020.

Asia 19 countries (n = 152 papers)	India (55), China (43), Pakistan (16), Bangladesh (6), Myanmar (1), Malaysia (3), Indonesia (2), South Korea (3), Nepal (6), Taiwan (3), Kyrgyzstan (1), Laos (2), Australia (2) Japan (2), Sri Lanka (1), Thailand (3), Mongolia (1), Vietnam (1), Kazakhstan (1),
Latin America 6 countries (n = 28 papers)	Brazil (23), Argentina (1), Central America (1), Colombia (1), El Salvador (1), Bolivia (1)
North America 2 countries (n = 15 papers)	United States (13), Canada (2)
Middle East 10 countries (n = 42 papers)	Iran (26), Saudi Arabia (2), Palestine (6), Syria (1), Israel (1), Yemen (1), United Arab Emirates (1), Bahrain (1), Jordan (2), Lebanon (1)
Europe 19 countries (n = 60 papers)	Turkey (12), Greece (11), United Kingdom (11), Spain (5), Italy (5), Switzerland (1), , Republic of Croatia (1), Romania (1), Denmark (1), Poland (4), Belarus (1), Republic of North Macedonia (1) Russia (1), Germany (1), Republic of Sweden (1), Serbia (1), Germany (1), France (1).
Africa 23 countries (n = 71 papers)	Tunisia (2), Egypt (7), Libya (2), Ethiopia (5), Botswana (3),, Lebanon (2), Ghana (6), South Africa (7), Malawi (1), Uganda (2), Kenya (3), Nigeria (16), Haiti (1), Cameroon (3), Morocco (2), Senegal (1), Somaliland (1), Algeria (1), Mauritius (2), Cote d'Ivoire (1), Zimbabwe (1), Sudan (1), Tanzania (1)

for 2014 and adopted from the published report of the EPI, 2020 by the Yale Center for Environmental Law and Policy (EPI, 2020).

The human development index (HDI) ranking of the countries is one of the best criteria for assessing human well-being, including long and healthy life, being knowledgeable, and having a decent standard of living, unlike the GDP which only focuses on the economic growth of the country. Life expectancy (LE) at birth in years shows the lifespan of a newborn infant from birth. Health expenditure (HE) spending per capita represents the total amount of GDP that expands on public and private health settings of the country. HDI, LE, and HE data are based on the year 2015 because we selected an average year to represent our dependent and independent variables. Details are shown in Table 3.

The medical waste generation rate of the countries was defined as the dependent variable, whereas the EPI of controlled solid waste management, HDI, HE, and LE, as independent variables for linear multiple regression modeling and Pearson and Spearman correlation coefficients for the analysis of correlation among the selected indices. The calculation was performed using the SPSS-26 software package.

3. Results

3.1. Status of research publications on medical waste management worldwide

The number of articles published on medical waste management practices in different countries from January 2000 to May 2020 is presented in

Table 3. Data on medical waste generation rate, environmental performance index (EPI) of controlled solid waste management, human development index (HDI), life expectancy (LE), and health expenditure (HE) per capita of GDP.

Region	Country	Medical waste generation rates (kg/bed/day)	EPI of controlled SWM (%)	Human development index -2015 (ranking)	Life expectancy at birth -2015 (year)	Health expenditure per capita (US$)
Asia	India	0.8	16.1	0.63	68.6	59.0
	China	0.6	51.8	0.74	75.9	392.8
	Iran	3.7	19.0	0.79	75.8	375.1
	Pakistan	0.3	31.1	0.55	66.6	37.9
	Bangladesh	1.1	5.0	0.59	71.5	31.8
	Indonesia	0.7	49.8	0.70	70.8	100.4
	Nepal	2.1	30.5	0.57	69.5	45.1
	Taiwan	1.9	0.0	0.00	0.0	0.0
	Sri Lanka	2.3	4.4	0.77	76.3	151.4
	Saudi Arabia	0.9	61.4	0.86	74.7	1243.6
	Palestine	0.8	0.0	0.69	0.0	0.0
	Japan	2.3	86.5	0.91	83.8	3733.7
	Jordon	2.5	43.1	0.72	74.1	314.3
	Korea	0.4	96.7	0.90	82.0	1925.5
	Kazakhstan	5.4	2.2	0.81	72.0	316.4
	Lao PDP	0.5	18.7	0.59	66.5	53.0
	Viet Nam	0.9	22.8	0.68	75.1	116.7
	Thailand	2.0	32.9	0.75	76.1	214.4
	Lebanon	2.5	61.4	0.73	78.8	655.8
	Malaysia	1.9	81.4	0.80	75.5	376.1
Africa	Libya	1.3	0.0	0.69	72.1	312.6
	Ethiopia	1.8	0.0	0.45	65.0	24.9
	Nigeria	2.5	7.7	0.53	53.1	97.8
	Cameroon	0.6	10.2	0.55	57.6	63.6
	Ghana	1.2	0.0	0.59	62.8	82.4
	Tunisia	0.8	39.6	0.73	75.9	268.2
	Algeria	1.0	91.6	0.75	76.1	290.5
	Mauritius	0.4	99.0	0.79	74.4	529.2
	Egypt	1.2	16.3	0.69	71.3	180.8
	Morocco	0.5	39.6	0.66	75.7	147.4
	Sudan	0.9	53.8	0.50	64.4	158.0
	Tanzania	1.8	0.0	0.52	63.1	32.1
Europe	Turkey	1.6	48.5	0.80	76.5	454.6
	Greece	0.3	83.0	0.87	81.0	1464.7
	Serbia	1.9	44.7	0.79	75.3	491.3
	Italy	4.1	83.7	0.88	82.5	2708.8
	Bulgaria	2.0	83.6	0.81	74.6	572.0
	Netherlands	1.7	100.0	0.93	81.5	4674.7
	Norway	3.9	97.6	0.95	82.3	7565.5
	France	3.3	94.8	0.89	82.3	4204.1
	Spain	4.4	89.0	0.89	82.8	2351.5
	Germany	3.6	97.9	0.93	80.6	4617.5
	Latvia	1.2	61.4	0.84	74.5	775.6
	United Kingdom	3.3	92.9	0.92	81.0	4326.3
America	Brazil	3.3	65.8	0.76	75.0	776.2
	Bolivia	0.5	31.1	0.69	70.3	201.6
	El Salvador	0.4	55.5	0.66	72.4	283.3
	Ecuador	2.1	53.6	0.76	76.1	528.2
	Canada	8.2	84.7	0.92	81.9	4539.1
	United States	8.4	48.3	0.92	81.0	9538.1

Note: Data for medical waste generation are collected from the systematic review and details are attached in the SI excel file. Only 50 countries have the data of medical waste generation rate, while other studied countries provide data related to medical waste practices and awareness. Data for HDI, life expectancy, and health expenditure per capita of GDP were adopted from the World Bank. The EPI of controlled solid waste management was adopted from (epi.yale.edu.).
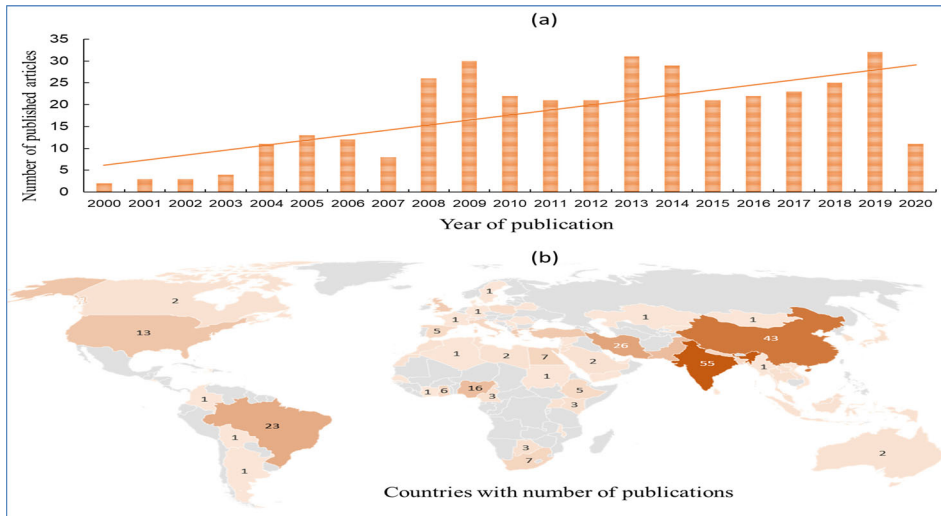
Figure 2. Number of medical/healthcare waste management articles a) published between January 2000 and May 2020 and b) the distribution of publications in each country.

Figure 2. The number of publications has significantly increased from approximately less than 5 in 2000 to approximately 30 in 2019 (Figure 2a). The results show that most of the countries with economies in transition have published a significantly higher number of publications compared to affluent countries. In Asia, India, China, and Iran have the highest number of articles published on medical waste management and practices. Nigeria in Africa, Brazil in Latin America, the United States in North America, and Turkey in Europe have the leading number of published articles. The higher number of publications in those countries could be an indication that these countries have severe medical waste mismanagement or environmental pollution, public health, and economic adversity directly related to medical waste (Islam, 2019; Akyı ldı z et al., 2017; Adu-Kumi–Jonathan et al., 2019).

3.2. Medical waste generation rate and EPI scores

The average medical waste generation rate in each country compared with the environmental performance index of controlled solid waste management in the respective country is presented in Figure 3. The results show that the generation rate of medical wastes in low and middle-income countries is significantly less than that in developed and high- income countries. Overall, the average waste generation rate ranges from 0.3–8.4 kg/bed/day. The United States and Canada generate the highest amount of medical waste (8.4 and 8.2 kg/bed/day, respectively). Kazakhstan and Iran, in Asia, generate the highest amount of medical waste (4.6 kg/bed/day), while in
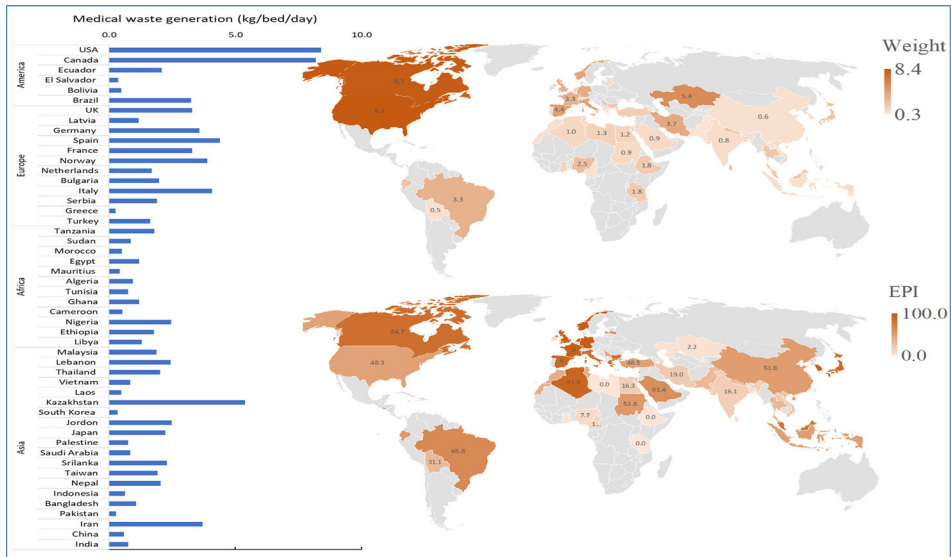
Figure 3. Amount of medical waste generated in different countries and their environmental performance index (EPI) of controlled solid waste management.

Europe, Spain and Italy generate the highest amount (4.4 and 4.1 kg/bed/day, respectively). Pakistan and Greece show the lowest amount of medical waste generation (about 0.3 kg/bed/day, each). Similar trends in the medical waste generation rate have also been observed in past studies, where countries with transitional economies have a much lower generation rate of medical waste as compared to affluent countries (Minoglou et al., 2017; Ansari et al., 2019; Windfeld & Brooks, 2015). This could be attributed to better healthcare services and an increasingly aging population in affluent countries utilizing the most healthcare materials and services. However, the recent economic transformation in developing countries has helped millions of people come out of poverty with access to better healthcare service. However, the current and postCOVID-19 pandemic demands for medical resources could be a potential cause for a rapid global increment in medical waste generation (Guterres, 2020; Rahman et al., 2020). .

Figure 3 shows the medical waste generation rate with the EPI scores of the controlled solid waste management for all the countries evaluated. The EPI scores of the controlled solid waste management in the studied countries vary significantly, from 0 in Tanzania, Ethiopia, Libya, and Palestine to 100 in the Netherlands. The results show that most affluent countries have higher EPI scores, while low and middle-income countries showed lower EPI scores. Therefore, despite having the highest generation rate of medical waste, affluent countries have better controlled solid waste management, and ultimately, the generated medical waste is properly disposed of (Zamparas et al., 2019). However, in low- and middle-income countries,
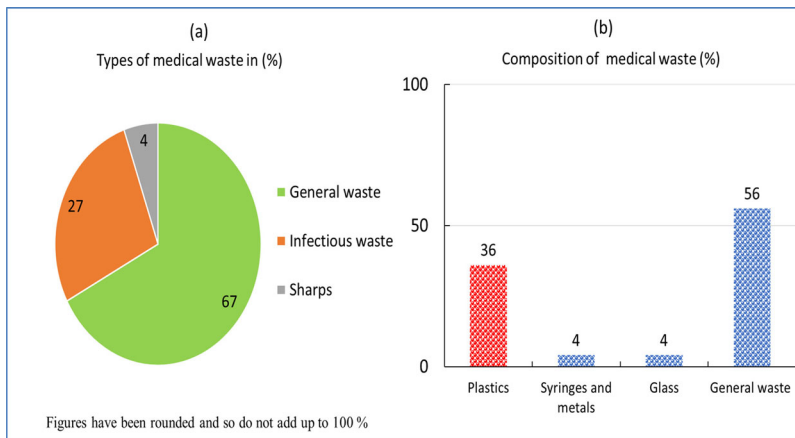
Figure 4. Average percentage of different types of medical waste and composition. Note: General waste refers to waste that does not pose any biological, chemical, radioactive or physical hazard, and contains organic waste such as food, clothing, paper, and wood.

the generated medical waste ultimately ends without proper management, despite having a lower generation rate. Juxtaposed to the above results, we found an exceptional case for the US, where the EPI score was very poor, even compared to many countries with economies in transition, and the generation rate of medical waste was recorded as the highest among the studied countries. The results show that although medical waste in the US is managed properly, it may not be environmentally sustainable. Alternatively, this could be attributed to the different regulations for medical waste in the US compared with the municipal solid waste (EPA, 2020a).

3.3. Medical waste types and composition

The average amount of medical waste and their composition are presented in Figure 4. The results show that the generated medical waste contained approximately 67% of general waste, 27% of infectious or toxic waste, and approximately 4% sharps. The composition of the waste revealed that approximately half of the waste contained general waste such as food, liquids, and paper. The second major part was plastic waste which with about 36% of the total generated medical waste. Glass waste and syringes only represent 4% and 4% of the generated waste, respectively.

3.4. Medical waste handling knowledge and awareness

The status and practices of medical waste, including risks of injury, knowledge awareness, and in-service training of workers, and segregation of medical waste at the source in the studied countries are presented in Figure 5.
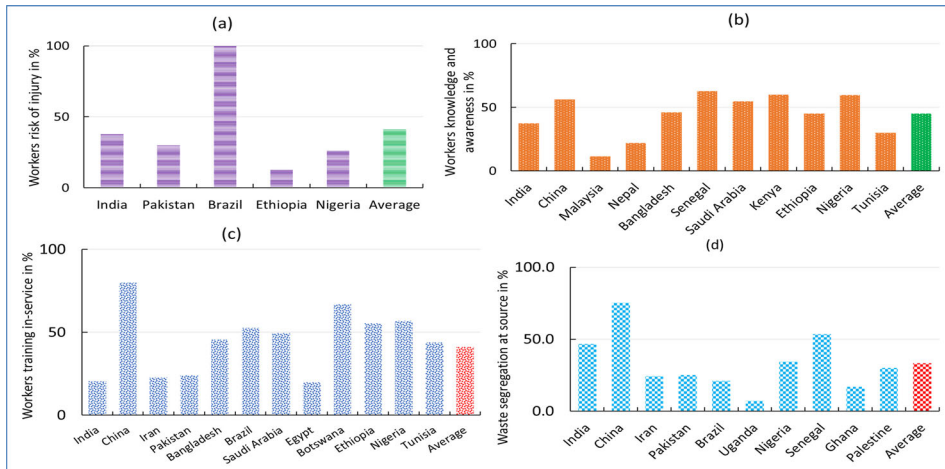
Figure 5. Management status and practices of medical waste in different countries. a) Risk of injury in workers involved in medical waste disposal in the studied countries; b) medical waste management knowledge and awareness among the workers in studied countries; c) the workers trained in-service for the medical waste management; and d) the quantity of medical waste segregate at the source.

The results show that on average about 40%c of workers have been injured during the handling of medical waste. In Brazil, most of the workers were somehow injured during the handling of medical waste, while in India, almost 40% of workers reported injuries, including eye, skin, and musculo-skeletal disorders. Figure 5b shows the worker's knowledge and awareness of medical waste disposal. The results show that on average about 45%of workers were well aware of medical waste disposal procedures and had good knowledge about proper handling of medical waste. In Malaysia, only 12% of workers were aware of proper medical waste management repre-senting the lowest rank among the studied countries, whereas Senegal had the highest percentage of worker with knowledge and awareness about medical waste disposal.

Figure 5c shows the number of workers who received in-service training for the handling of medical waste. The results show that on average, 41% of the workers received in-service training for proper handling of medical waste. Among the studied countries, China shows the highest number of workers that were trained, representing an average of 80%. India and Egypt showed the lowest in-service training, with an average of 20% in each country. Figure 5d shows the quantity of medical waste segregation in the studied countries. The results show that on average about 33% of the med-ical waste was segregated at the source. China segregates approximately 75% of the total medical waste, while Uganda and Ghana only sorts l 7% and 17% of their total medical waste, respectively.

Table 4. Descriptive and normality test results of the medical waste generation rate in the selected regions.

Region	Sample Size	Mean ± St. Dev.	Kolmogorov-Smirnov		Shapiro-Wilk	
			Statistic	Sig.	Statistic	Sig.
Asia	20	1.7 ± 1.3	0.365	0.012	0.696	0.006
Africa	12	1.6 ± 0.7	0.205	0.200	0.946	0.71
Europe	12	2.4 ± 1.2	0.312	0.070	0.879	0.264
America	6	5.3 ± 3.6	0.223	0.200	0.831	0.109
Overall	50	2.3 ± 1.3	0.365	0.012	0.696	0.006

Note: Only 50 countries have the data of medical waste generation rate among the studied 78 countries.
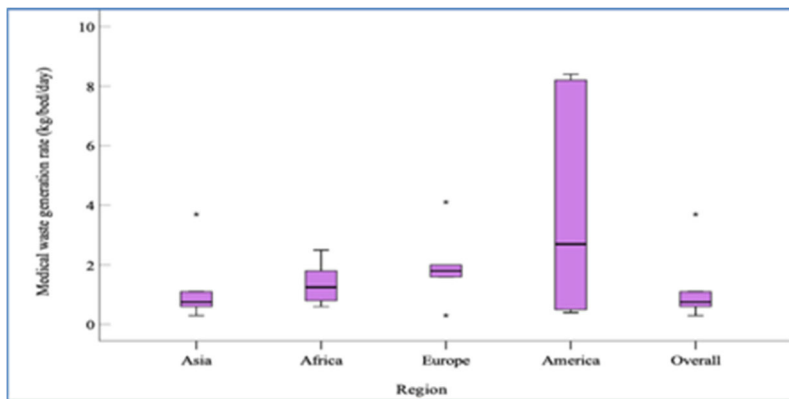
Figure 6. Boxplot representing the overall and country specific medical waste generated in different regions.

3.5. Correlation of medical waste generation with the selected indices

The descriptive and normality test results of the dependent variable (medical waste generation rate) in the selected regions was analyzed using the Kolmogorov-Smirnov and Shapiro-Wilk normality tests are presented in Table 4. In Figure 6, we present the mean value of the generated medical waste in each region. The results of the KS test show that the values of Europe and Africa are well distributed compared to Asia and the overall value of all regions. The values of America show the lack of normal distribution, probably related to the exceptionally high quantity of medical waste generation (an average > 8 kg/bed/day) in the US and Canada compared to other Latin American countries.

The correlation between the weight of medical waste generated and the four possible indices that might influence the generation and disposal of medical waste in different regions are presented in Figure 7. The correlations were studied by both the graphical representation and the Pearson and Spearman coefficients; the detailed outcome is included in the SI Excel file. Figure 7b–d shows a positive correlation between the medical waste generation rate and HDI, LE, and HE of GDP ($R^2 = 0.24$, 0.15, and 0.46). These positive correlations can be expected and are in accordance with
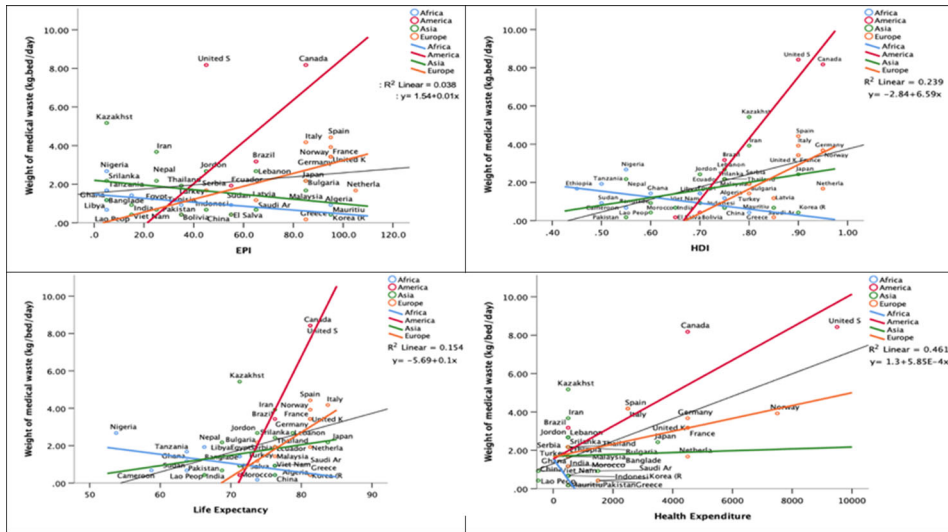
Figure 7. Correlation between the dependent variable (weight of generated medical waste) and independent variables (EPI, HDI, LE at birth, and HE of GDP) in the studied countries. (Note: the regional color regression lines show the outcomes of the trend of the independent variables in the region, while the value of R is constructed from the overall data.).

previous studies (Minoglou et al., 2017; Ansari et al., 2019; Windfeld & Brooks, 2015). The HDI, LE at birth and HE of GDP are indicators of a healthy lifestyle, which may be directly related to a well-established health-care system and sufficient medical equipment and materials. Ultimately, these facilities and services consume more materials to provide better service to the population and thus are also responsible for higher medical waste generation.

Similarly, a positive correlation also observed in the Pearson and Spearman coefficients, the details are included in the SI Excel file. In the case of EPI indices and their correlation with medical waste generation, the graphical values are not positively correlated to the dependent variables, but Pearson and Spearman values show a significant correlation. This could be attributed to a lack of sample value distribution, as shown in Figure 6. However, Figure 7a shows that the correlation between medical waste generation and EPI was not significantly correlated. The EPI scores suggest that the controlled solid waste management has no direct connection to the generation of solid waste. However, Figure 7a shows that the EPI scores in the US and Europe are higher than countries with economies in transition in Asia and Africa. These trends, like those shown in Figure 3, demonstrate that affluent countries produce a higher amount of medical waste due to a higher HDI, LE, and HE scores, and at the same time having a positive correlation with EPI scores revealed that most of the generated waste in these countries is properly disposed. However, the EPI scores of many

countries with economies in transition, as shown in Figure 7a, have a negative correlation with medical waste generation. Therefore, the medical waste generated, particularly in Asia and Africa, despite having a lower generation rate than that of affluent countries, has not been disposed of properly.

4. Discussion

To the best of our knowledge, this study is the first comprehensive meta-analysis of medical waste management practices, including medical waste generation rates, types, and composition. We included the respective knowledge and awareness of the workers who are responsible for the disposal of medical waste, including source segregation in 78 countries, covering most of the regions. The results show that the workers involved in the medical waste disposal and management system have not been well-trained and showed limited knowledge and awareness of handling medical waste. The average amount of segregated medical waste at the source was less than 40% of the total waste generated medical in the studied countries. The content of medical waste also varies, and the content of plastic waste represents almost 36% of the total generated amount.

The proper management and safe disposal of medical waste amid the COVID-19 pandemic is, therefore, a vital element in an effective emergency response that requires proper identification, safe collection and separation, storage and transportation to treatment plants and disposal sites, and safe practices including disinfection, and proper training of healthcare workers (WHO, 2020c; UNEP, 2020a; ADB, 2020). However, the findings of our study showed the absence of holistic approaches and inadequate technological adaptation that could accelerate the integration of medical waste management into a prospective circular economy (Kulkarni & Anantharama, 2020; Kyriakopoulos et al., 2019). A situation exacerbated by the lack of knowledge and awareness among medical waste workers and limited financial resources to ensure safe medical waste management, particularly in countries with economies in transition. The results highlight the poor management of medical waste in low and middle-income countries, as previously reported (You et al., 2020; Zar et al., 2020).

In many countries, where the safe disposal of medical waste either does not exist or is not well established, medical waste is often mixed with general household waste and treated as municipal solid waste either by incineration or is disposed of in open landfills (Singh et al., 2020a). In low and middle-income countries, the incineration plants used for medical waste treatment are often equipped with old and unsafe technologies that cause further heavy metal pollution and dioxin emissions. Studies have reported

that the emission rate of these toxins could go as high as 40,000 times higher than the Stockholm Convention's emission limits (Datta et al., 2018; UNGA, 2011). In addition, medical waste treatment practices in many countries with economies in transition are unregulated and often neglect the WHO guidelines for proper disposal of medical waste. Additionally, unlike hazardous and mercury waste which are covered under the international treaties such as Basel, Minamata, Rotterdam, and Stockholm Conventions, there is no international standard that directly covers medical waste management (Kühling, 2014; UNEP, 2020b) Therefore, in the absence of global regulatory procedures of medical waste, most countries have their own set of guidelines, and they vary substantially in each country. According to WHO reports, the unsafe disposal and management of medical waste not only causes environmental pollution and public health risks but also have implications for human rights due to the little attention paid by international communities (Stringer, 2011; Seck, 2012).

Although medical waste has not been properly managed and safely disposed of in many countries, the fact is that there are potential solutions that could address the challenges of medical waste in many countries with economies in transition. It particularly depends on the acceptance and finance of advanced technologies for the treatment of medical waste and the adaptation of sustainable concepts that are used in many developed and industrial countries. The first step for proper management of medical waste is source reduction, (i.e., minimization of waste production), and proper segregation at the source, as recommended by the WHO. If segregation is difficult and cannot be separated from general waste then it must be treated as medical waste. (Singh et al., 2020b; WHO, 2020a; UNEP, 2020a) Most importantly the success of the healthcare waste management system is also a key part of the UN Sustainable Development Goals including SDG 3-Good health and wellbeing, SDG 6-Clean water and sanitation, SDG 8-Decent work and economic growth, SDG 12-Responsible consumption and production and SDG 13 Climate action (HCWH, 2020).

The success of the medical/healthcare waste management will certainly accelerate the progress toward meeting the above-mentioned goals by 2030. Good health and wellbeing are essential for sustainable development, and these are, directly and indirectly, related to the unsafe disposal of medical waste, which is responsible for about 5.2 million lives, including 4 million children annually, and millions of workers involved in handling medical waste are being infected with many infectious diseases such as HIV, hepatitis B, and hepatitis C (WHO, 2018; TheDailyStar, 2020). The SDG 8 aims to access to employment to the poor socioeconomic class to alleviate poverty. This is directly related to workers handling medical waste, who are often underpaid and work in an unsafe environment with no or limited in-

service training, which was demonstrated in this study. Medical/healthcare waste must be recognized as an essential public service, with proper standards, training, vaccinations, and good living conditions, particularly in low- and middle-income countries. The SDGs related to clean environment and sustainable consumption must target pollution reduction and health impacts through environmentally safe management of all waste, especially for medical waste, throughout the product life cycle by minimizing the production, source segregation, avoiding incineration, and recycling and reusing all the resources and energy (HCWH, 2020). There is an urgent need for countries to adopt a safe medical waste disposal system to prevent the stockpile and to prevent communities from being contaminated with potentially infectious medical waste. Despite these challenges for the implementation of environmentally sound management of medical waste, there are solutions that can be implemented by developing and adopting treatment technologies, products, and concepts that will help drive the medical system forward to a circular economy concept. The linear model of planned obsolescence is one in which medical products are designed for single use; interestingly, a composition that includes plastics is about 36%. This single-use model needs to be replaced by a circular concept, where the designed products, especially plastics, are returned to the manufacturing stage after use to make a circular flow of the materials (Payne et al., 2019).

5. Conclusion

Through this study, we discovered that a large amount of medical waste generated in healthcare settings worldwide are not properly managed, and workers involved in medical waste management practices lack important knowledge and awareness of safe practices. Among the countries included in this study, only 45% of workers were aware and knowledgeable about proper medical waste management. Approximately 40% of the workers were injured during waste handling, including musculoskeletal disorders, eye injury, skin infection, and disability. The generation of medical waste averaged 2 kg/bed/day, ranging from 0.3 to 8.4 kg/bed/day, which includes an average 67% representing general waste, 27% infectious or toxic waste, and 4% sharps. Plastics represented about 36% of the total generated waste. On average only 33.4% of medical waste was segregated in the studied countries and on average only 41% of workers were trained in-service for medical waste disposal. Additionally, the study revealed that there is a positive correlation between the medical waste generation rate and HDI, LE, and HE because these indices represent a better quality of life and healthcare services. The negative correlation between medical waste generation and EPI scores was shows positive outcomes for the countries that produce

medical waste due to their higher EPI scores, compared to countries with economies in transition where the safe disposal of medical waste is scare. The results warrant an immediate call for collective, voluntary, and effective measures to be initiated for environmentally sustainable management of medical waste, particularly in countries that are currently dealing with the COVID-19 pandemic.

Contributors

NS, OAO, and YT initiated the work. NS collected the data and did the initial search. NS and YT independently reviewed the publications. NS wrote the first draft, and OAO wrote the final draft. YT supervised the study, and all authors independently reviewed and approved the final draft manuscript.

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